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Adding value to physics labs to help build confident, knowledgeable teachers

Lorna Jarrett
University of Wollongong, lornaj@uow.edu.au

Brian Ferry
Univerity of Wollongong, bferry@uow.edu.au

George J. Takacs
University of Wollongong, gjt@uow.edu.au

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Lorna Jarrett' and **Brian Ferry**,
Faculty of Education, University of Wollongong, Australia
George Takacs, Faculty of Engineering, University of Wollongong, Australia
lorna@uow.edu.au, bferry@uow.edu.au, gjt@uow.edu.au,

Abstract: *This pilot study is being conducted by an interdisciplinary team and is funded through the University of Wollongong Education Strategies Development Fund. The project focuses on the first-year physics laboratories of pre-service teachers enrolled in Bachelor of Science Education degrees. It aims to make the laboratory experience more aligned to the needs of future science and physics teachers, contributing to their confidence in using apparatus in the classroom and their effectiveness as communicators who can explain concepts fluently from a background of deep understanding. According to Mulhall (2006) and Johnston and Millar (2000), misconceptions are common even among successful physics students and explicit teaching strategies that address conceptual change are needed to correct misconceptions. However, our approach is also of value to general physics students.*

Our approach has three strands. The first involves identifying experiments in our labs that have content in common with compulsory practical investigations in the NSW year 11 / 12 physics syllabus. Experimental procedures and instructions for these labs are being modified to create explicit links between concepts, apparatus and procedures in the first-year labs and those in the school syllabus. Secondly, we are incorporating peer instruction using qualitative multiple-choice questions designed to probe conceptual understanding. These will be included in the laboratory manual, at strategic points in the experimental procedure. Students will discuss and agree on responses before proceeding with the experiment. This approach is based on the work of Mazur (1996), Crouch and Mazur (2001) and Cox and Junkin III (2002) who reported that it developed confidence in communication and was effective in challenging misconceptions. Finally, in designing the laboratory manual we will employ principles of Cognitive Load Theory to decrease extraneous cognitive load and make learning more efficient (Chandler & Sweller, 1991; Paas, Renkl & Sweller, 2004; Purnell, Solman & Sweller, 1991). Our project will run from February 2009 until January 2010. Syllabus mapping has been carried out to identify appropriate experiments for the study, and three have been selected. High school physics teachers have been interviewed to discuss corresponding practical investigations in the school syllabus and findings are being used to inform the modifications to the procedures and manual for our laboratories, which will run in Spring Session 2009. The impact of the modified experiments will be compared with that of the unmodified experiments, and with previous years' results. This conference paper elaborates on the theoretical background of our strategies and reports on our progress.

Project aims

This pilot study focuses on pre-service science and physics teachers, however the majority of modifications would be beneficial to general first year physics, chemistry and biology laboratories. The project aims to help prepare pre-service teachers to teach practical investigations in the NSW physics syllabus for years 11 and 12; to challenge misconceptions, link theory to experiment and develop deep understanding of concepts; and to foster confident communicators. Our approach comprises incorporating explicit links between experiments in the first year laboratories and practical investigations in the NSW physics syllabus for years 11 and 12, peer instruction strategies and the application of Cognitive Load Theory to the format of the laboratory manual.

Need for the project

A number of factors prompted us to focus on the first year physics laboratories for our pre-service teachers enrolled in Bachelor of Science Education degrees. Firstly, physics teaching in Australia and worldwide is in crisis. Harris, Baldwin and Jensz (2005) detail the struggles that schools face to find suitably qualified physics teachers and assert that tertiary institutions share the responsibility for addressing this looming crisis. Secondly, pre-service teachers have different needs to other BSc students. They will be responsible for laying the foundations of understanding of hundreds of physics students, so the quality of their own conceptual understanding is of utmost importance. However, unlike other physicists, they are increasingly likely to be the most qualified and knowledgeable individuals in their workplace, so any misunderstandings they have are likely to go unchallenged and be passed on to their students. Toh, Ho, Riley and Hoh (2006) confirm the importance of pre-service teacher preparation: they found that it had by far the greatest influence on school students' achievement when compared to class size, streaming, or amount of homework. According to Harris (2007; p. 25) 'Aspiring science teachers need tertiary preparation that provides them with the disciplinary knowledge appropriate to the teaching that they will do'. Thirdly, considerable evidence exists that misconceptions are common even among successful physics students; that traditional teaching methods including 'cookbook' laboratories, are not effective in overcoming misconceptions; and that strategies involving active engagement and peer interaction have the greatest potential for improving learning (Johnston & Millar, 2000; Mulhall, 2006). According to Thacker (2003; p. 1839), widespread concerns exist about the suitability of traditional teaching methods because pre-service teachers "often do not gain a solid conceptual understanding". It should be stated however, that these issues do not apply only to students enrolled in teaching degrees: many other students will teach physics at some stage in their careers, as teachers, tutors, demonstrators or lecturers. Also, sound conceptual understanding is arguably important for all physicists.

Effective learning in laboratories

We reviewed literature on student learning in science and physics laboratories in order to understand the problems and identify research on strategies for overcoming misconceptions. The most frequently cited problems are lack of meaningful discussion and engagement, with students focusing on completing a list of tasks without necessarily understanding them; and failure to link experimental practice to underlying theory and concepts (Aufschnaiter & Aufschnaiter, 2007; Domin, 2007; Mestre, 2001). One study by Cox and Junkin III (2002) specifically set out to tackle misconceptions in the laboratory. Their strategy for increasing cognitive engagement in introductory physics laboratories was based on the peer instruction methods of Mazur (1996). Multiple-choice conceptual questions were integrated into the laboratory manual and groups of students who had chosen different answers were directed to discuss their ideas before continuing with the procedure. Pre- and post-tests revealed a difference in learning gain of 50% to 100% between experimental groups and control groups, who had answered the conceptual questions individually but had not discussed them in groups.

Cognitive Overload as a barrier to effective learning in laboratories

Domin (2007; p. 150) notes that the excessive amount of information in 'cookbook' laboratory manuals and the task of separating relevant information from extraneous content, often imposes considerable demands on students' working memory, leading to 'working memory overload'. Cognitive Load Theory asserts that humans have essentially unlimited long-term memory but a limited working memory, which can process typically no more than four elements at a time. Working memory limitations apply to novel information, but when information is successfully transferred into long-term memory, large amounts can be handled as one element in working memory (van Merriënboer & Sweller, 2005). If too much novel information is presented at once, then working memory becomes overloaded, and effective learning fails to occur (Sweller, 1994). Cognitive load can be characterised as intrinsic, ie: imposed by the nature of the information to be learned, extraneous, ie: imposed by the format of instruction and unrelated to the information to be learned, and germane, ie: imposed by the format of instruction but relevant to learning (Paas et al. 2004). Research associated with Cognitive Load Theory suggests that extraneous cognitive load can be reduced through the appropriate design of learning materials (Purnell et al. 1991; Chandler & Sweller, 1991). As our project involves increasing the amount of background material and activities in laboratories, it is necessary to 'take something out'. By applying Cognitive Load Theory to the format of the manual we will reduce extraneous cognitive load, compensating for the increase in germane cognitive load imposed by reading background material and discussing concept questions.

Progress to date

Syllabus Mapping

Syllabus mapping was carried out to identify areas of correspondence between prescribed practical investigations in the NSW year 11 / 12 physics syllabus and our first year physics laboratory schedule. Three experiments were selected for the study. These are: using a closed, resonating air column to calculate a value for the speed of sound in air; electrical properties of a photocell; and internal resistance of voltmeters and ammeters.

Consultation

Other Tertiary institutions

We contacted other tertiary institutions to determine whether any had modified first year physics laboratories for students enrolled in double degrees. Of the ten who have replied to date, only one makes different arrangements. In this institution, pre-service teachers use the same facilities as other physics students but staff with an education-related background supervise the laboratories and help students to link their laboratory experience to their learning in Education classes and on practicum placement.

Practicing physics teachers

One of the aims of our project was to help pre-service teachers learn to use apparatus and methods which they would be using in their future careers, so it was important to understand how these practical investigations are actually carried out in schools. Budget constraints precluded large-scale consultation; however three experienced physics teachers from local schools participated in interviews. We discussed their approach to teaching the selected investigations, problems they had encountered, possible alternative procedures and the reasons for their choice of procedure, and the investigations' impact on students' understanding. Two investigations were carried out as we had expected and involved similar equipment to that already used in our laboratories. However, the third investigation was not carried out by the teachers interviewed, but was replaced with an investigation that we considered lacked validity. The reason for this substitution was that concepts beyond the scope of the NSW physics syllabus were required in order for students to understand the procedure. We had stated at the outset that modification of our labs would only take place if we were satisfied that the procedures carried out in schools were sufficiently valid. Therefore, we decided not to modify the procedure for this experiment, but to provide background and scaffolding to help pre-service teachers to carry out the investigation in schools.

Reformatting the laboratory manual

Strategies to overcome misconceptions and enhance communication skills

We decided to incorporate the approach of Cox and Junkin III (2002), as it has the potential to meet a number of our requirements. Firstly, peer instruction has proven effective as a technique for overcoming misconceptions in physics (Crouch & Mazur, 2001; Fagen, Crouch & Mazur 2002; Mazur, 1996; Mulhall, 2006). The technique involves students answering mostly qualitative, multiple-choice questions then discussing their responses with other students until they agree on an answer. Interactive engagement (Thacker, 2003), and the construction and peer evaluation of qualitative arguments (Mestre, 2001) have been recommended as strategies for enhancing conceptual understanding. Secondly, the approach requires students to discuss and defend their understanding, thereby helping to build confidence in communicating. Cox and Junkin III (2002) assert that peer instruction improved critical thinking and communication skills in their students. Peer instruction can be incorporated into the labs without significant restructuring or changes to format, and our small cohort of ten students means that organising students into groups for discussion will not require software such as that used by used by Cox and Junkin III to collect student responses. Questions will be inserted at points in the experimental procedure where key concepts appear, or where past research (Driver, 1985; Gilbert, 1977) informs us that misunderstanding may occur. Mazur (1996) recommends allowing up to four minutes for student discussion, so no more than five questions will be incorporated into each experiment.

Appropriate concept questions are unambiguous and target key concepts, students should not be able to solve them by resorting to formulae or memory, and 35% to 70% of students should answer them correctly at first attempt. Multiple-choice questions reduce the time spent wording answers, and distractors should involve common misconceptions, such as those previously observed in student work (Cox & Junkin III, 2002; Crouch & Mazur, 2001; Mazur, 1996). Berry, Mulhall, Gunstone and Loughran (1999) suggest that predicting the outcome of experiments increases cognitive engagement. Cox and Junkin III (2002) required their students to make predictions, describe their observations or explain observations and results. According to Mestre (2001; p. 49), it is important for prospective teachers to learn about the process of science, 'using equipment to design experiments and test hypotheses', but research casts doubt on the effectiveness of such discovery-based approaches (Domin, 2007; Kirschner, Sweller & Clark, 2006). However, the inclusion of concept questions about experimental aims, hypotheses, choice of apparatus and experimental design is anticipated to increase students' understanding of science as a process.

Application of Cognitive Load Theory to the laboratory manual format

We met with Professor John Sweller, the originator of Cognitive Load Theory, to validate our approach to re-formatting the laboratory manual. The most significant aspect of Cognitive Load Theory for our project is the split-attention effect (Purnell et al., 1991), where Cognitive Load is generated by the need to mentally integrate diagrams and text that cannot be fully understood separately. For the first experiment, resonance in closed columns, we removed a set of diagrams representing standing waves in open columns, as these are not involved in the procedure. We enlarged the diagrams for closed columns and integrated explanatory information and formulae onto them, taking the required information from paragraphs on the facing page. Information on the end correction, which had been spread over three sections and two pages, was also integrated into one labelled diagram. A written description of the procedure for determining the speed of sound by graphing the data was replaced with a labelled exemplar graph. Instructions for using an oscilloscope, which consisted of a photograph of an oscilloscope with controls numbered and accompanying text explaining the function the numbered controls, were replaced with a labelled diagram showing the function of each of the controls.

Other modifications – background and linking theory to experiment

Each of the modified experiments includes a reference to the related practical investigation in the NSW year 11 / 12 syllabus. For the first experiment we added diagrams representing longitudinal and transverse waves and the generation of standing waves through reflection and superposition. Again, the diagrams were labelled with the information needed to understand them. The diagrams of standing waves in pipes were rotated, making them vertical rather than horizontal, and pipe length rather than wavelength was changed, to show how different numbers of wavelengths can result in resonance. These changes mean that the diagrams correspond more closely with the actual apparatus and procedure. The formulae were re-arranged to make column length the subject: this corresponds with the formulae used in calculations.

Evaluation of the project

Because of our small cohort of ten students it is not feasible to run experimental and control groups for our modified experiments. However, we intend to increase the credibility of our results through triangulation. Evaluation will involve comparison of student responses to concept questions before and after discussion, observation of student interactions during the laboratories, interviews with students and statistical comparison of laboratory marks between participants, previous Bachelor of Science Education students, and the 471 students doing unmodified laboratories. Ethics approval and participant consent was obtained for teacher interviews, modifications and data collection from students.

Preliminary results and discussion

To date the first modified experiment, determination of the speed of sound, has run. Not all data for the evaluation of this experiment are as yet available: this section is based on observation of participant interactions in the laboratory, and examination of participants' work. To test if the modified instructions resulted in improved marks we performed two one-tailed independent sample t tests, equal variance not assumed. Participants' performance was compared with that of 62 randomly-selected students in the regular first-year laboratories. There was no significant difference between the two groups for an experiment where both used unmodified instructions ($t=1.20$, $p >0.05$, 1 tailed), but there was a significant difference between groups using unmodified and modified instructions for the speed of sound experiment ($t=3.34$, $p <0.01$, 1 tailed). Three concept questions were added to the experimental instructions. The first two, shown below, tested understanding of the theory section, and preceded experimental activities.

Question 1: At the point in the tube where the air column meets the water, the air pressure is:
A at a maximum
B at a minimum
C varying between maximum and minimum values
D constant

Question 2: The data points from the two tuning forks will lie:
A on the same line
B on two parallel lines
C on two lines that are not parallel but intersect
D on two lines which are not parallel and which do not intersect

For question 1, participants were equally divided between A and D, and were directed to discuss with a participant who had chosen a different answer. Although one participant initially expressed impatience to "get on with the prac", enthusiastic discussion ensued. Two participants independently deduced the correct answer (C) from the background material supplied and explained their understanding to the others. As all but one participant chose C for question 2, the demonstrator explained the correct answer (A), and participants expressed satisfaction with their understanding of it. However, a similar question in the results section of the experiment was answered correctly by only 60% of participants, and only 20% gave answers suggesting sound independent understanding. This suggests that the newly-acquired knowledge had not been transferred from short-term memory. Fourteen minutes of the two hour laboratory were spent on discussion of concept questions: this was significantly longer than anticipated, and the difficulties with calculations described below meant that there was not sufficient time for the third concept question to be discussed. The participants' only significant problem with interpreting instructions involved calculations using a supplied formula, which was given on a diagram on another part of the instructions and had to be re-arranged for the calculation. This calculation section had not been modified to reduce cognitive load, as modifications had focussed on integrating diagrams with explanatory text to reduce the split-attention effect. This could be improved by adding a worked example of the calculation for students to follow, and ensuring that all necessary formulas and information were supplied at the point where they were to be used, even if this meant repetition.

Conclusions

Results to date confirm the value of peer instruction for engaging students and overcoming misconceptions. Participants evidently enjoyed their discussions, reflected on their ideas and worked co-operatively to construct understanding. Misconceptions that may have gone unnoticed, were voiced and challenged. The concept questions were evidently too difficult as none of the participants initially answered them correctly, although this did not prevent participants from reaching the correct answer. However, discussions took up a significant amount of time, suggesting that in a two-hour laboratory, a maximum of three questions should be discussed.

With the limited data available to date, it is difficult to ascertain the effectiveness of the changes in format designed to reduce cognitive load. Statistical tests show a significant difference in marks between users of modified and unmodified instructions. This could be due to marker effect, and when more data is available samples will be selected from matched markers to minimise this. As stated previously, the participants' failed to apply what they had learned from Concept Question 2, to a question later in the experiment. In order for new knowledge to be transferred into long-term memory, rehearsal is required. This could be achieved by having students summarise their reasons for changing their answer to a concept question, although again this would require time. It should be noted that participants had not studied the topic prior to the laboratory and are unfamiliar with the graphical methods used, and therefore the intrinsic cognitive load associated with this laboratory is very high. Therefore, the reduction in cognitive load effected by the formatting of the diagrams alone, may not have been sufficient to reduce participants' cognitive load to a level where effective learning could take place.

Future Directions

Findings from the first modified experiment and participant feedback will be used to inform the modification of the next two experiments. Cognitive Load Theory will be used both for the formatting of diagrams and in the provision of worked examples where students are required to do calculations, so as to reduce the cognitive load of the instructions as much as possible. All formulae will be presented at the point in the instructions where they are to be used. Where possible, spreadsheets will be used to reduce the time spent on repetitive calculations. Concept questions will be written following work with students in the regular first-year physics laboratories: questions are anticipated to target the misunderstandings and queries most commonly voiced. Where possible, questions will also be tested by these students to ensure an appropriate level of difficulty. Following completion of the three modified experiments, the data collection and analysis described previously will be completed. If successful, we intend to apply our approach in other first-year laboratory classes.

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